TRANSACTIONS OF
THE
OPTICAL SOCIETY

VOL. XXII. 1920-21 No. 4.

THE TESTING OF HELIOGRAPH MIRRORS AND THE MEASUREMENT OF MIRRORS OF LONG FOCAL LENGTH

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MS. received, 4th April, 1921. Read, 14th April, 1921.

Abstract. The method of testing the general surface consists in observing the reflection from the mirror of a system of squares on the test board, the magnification given by the mirror being utilised to determine the curvature. The method of examination is applicable to the rapid measurement of mirrors of long focal length, especially of those forms silvered on the back, cata-dioptric mirrors, where the usual methods of measurement, test planes or spherometers, are inapplicable. Defects of curvature and distortion, astigmatism, and striae in the glass can be detected, and also defects of silvering and bad polishing.

(1) In warfare it is important that secrecy be maintained as far as possible, and as pointed out in the *Signalling Training Manual* the heliograph is capable of sending signals with a reasonable amount of secrecy if the mirror is kept nearly optically flat; under these conditions the spread of the reflected rays amounts to 98 yards at a distance of 6 miles, a spread due to the sun having a mean angular diameter of 32 minutes of arc.

(2) If the mirror is distorted or has an irregular surface the spread of the reflected rays increases at a rapid rate, the beam is scattered broadcast and the signals may be read in all directions; moreover the penetration or the carrying distance is diminished.

(3) The quality of a mirror may be tested by observing the reflection of some definite object, and a system of squares has been taken as the usual test object; the general quality of the whole surface or any part of it can then be seen by noting whether the squares on reflection appear distorted, either as a whole or locally. Such a test object may be used to give exact details of the curvature of a mirror

from which the spread and relative intensity of the reflections may be calculated at any distance.

(4) The perfect mirror is of course flat with an infinite radius of curvature, but for the purpose of examination it is desirable to impose certain limits of curvature within which mirrors may be considered satisfactory and outside of which mirrors should be rejected. The limits of curvature which have been adopted are 1000 ft radius for convexity and 500 ft for concavity; greater or less tolerance might be permitted according to circumstances, but the above limits are such as can be attained in workshop practice without straining for ultra optical performance.

(5) Now since we are dealing with unusually long focal lengths which must be rapidly measured, and further, the mirrors rarely have either side plane but in general correspond to lenses silvered on one surface, it is not practicable to use test planes or spherometers, but by making use of a magnification method, it is possible to observe both quickly and accurately whether the mirrors have focal lengths between the specified limits. For this purpose two circles are drawn on the test chart and these act as limit gauges; by taking up a suitable observing position the reflections of these circles may be optically fitted on the mirror much in the same way as any mechanical limit gauge is applied. The diameters of the circles are calculated as shown later for any diameter and focal length of mirror under test.

(6) The method of testing is as follows: The mirror is placed on an adjustable stand so that it may be directed to reflect the rays nearly along the path of incidence. The test board with its squares (usually 1 inch) and circles is set up some distance away (usually 50 ft) and facing the mirror. The test board is well illuminated and the observer stands on one side of the board and views the reflected image, using either the naked eye or a telescope the magnifying power of which may vary according to the degree of accuracy required. It is convenient, if the magnifying power of the telescope is more than six, to have an adjustable stand to hold the telescope so that the image of the test chart may be placed concentrically with the periphery of the mirror. Another convenience is an iris diaphragm fitted to the object glass end of the telescope so that full or diminished aperture may be used; the use of this will be explained later when considering the optics of the test.

(7) If the mirror is a good one, the reflection of the test board will be undistorted and along any one diameter twice the number of squares are seen as the mirror is inches in diameter plus a slight margin having a width the diameter of the objective of the observing telescope.

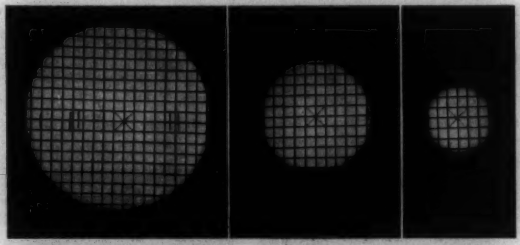
In Fig. 1 test rings were not drawn on the board, because in testing mirrors of various sizes it is often more convenient to have marks which are readily moveable to agree with the altered conditions of the test; such marks will be seen in the figure indicating where the circles should be drawn.

(8) If the reflection of the squares is distorted or the rings appear to lie outside or inside of the boundary of the mirror then the mirror is irregular in figure or is too concave or too convex to be satisfactory for signalling (Fig. 2).

(9) *Defective Mirrors.* There are a variety of defects in mirrors which may

make them unsuitable for signalling purposes, viz., irregularity of surfaces, bad silvering, want of glass surface polish before silvering, veins in the glass, astigmatism and curvature.

(10) *Irregular Mirrors.* The most common defect is that due to irregular surfaces; every degree can be found from that giving violent distortion, both local and general, to that exhibiting gentle undulations of the reflected test chart. The



9½ ins. 5½ ins. 3½ ins.

Fig. 1. Showing the comparative appearances of good mirrors of 9½, 5½, and 3½ inches diameter respectively.

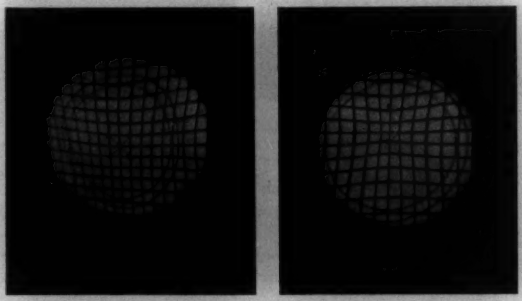


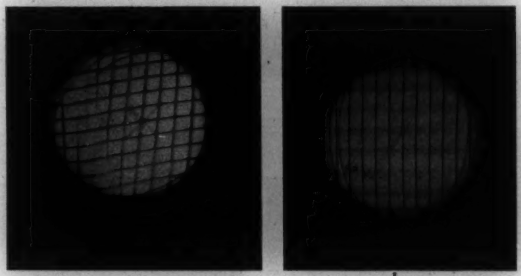
Fig. 2. Appearance of the reflected squares and circles seen in irregular mirrors of 9½ and 5½ inches diameter.

slight undulations, often local, are usually caused by attempts to polish out sleeks and scratches, thus producing slight hollows. It is only in mirrors not optically worked that violent distortion will be found, but optically worked mirrors may spring on removal from the polishing block and assume a figure not at all desirable. The defect of irregularity is serious because, not only are the rays rendered divergent, causing loss of penetration, but all the advantages of secrecy are lost,

for the reflections may be spread over a wide angle and stray beams become separated from the main beam, allowing the signals to be read in other places than intended.

(11) *Bad Silvering*. This is a defect which, if at all serious, can be readily detected; even a poor silver film is highly reflective but the deterioration of silver films is usually progressive and its first stage needs critical examination. The light grey patches which are the precursors of decay need for their detection a somewhat subdued light, such as that reflected from a white ceiling or transmitted through translucent celluloid, but it is frequently troublesome to get the correct angle of reflection—which is somewhat oblique—that shows the spots to the best advantage.

(12) *Bad Polish, grey, short of finish*. The defect of greyness is frequently met with; it is due to silvering on a surface lacking final polishing, or polishing at too early a stage before the surface is ground fine enough. Such surfaces appear at



a *b*

Fig. 3. (*a*) Showing effect of mirror with a vein in glass. (*b*) An Astigmatic Mirror.

a casual glance fairly good, but an examination of the test chart gives it an appearance of being seen through a fog and, even if the greyness is slight, crispness of definition is at once lost.

(13) *Striae*. If the glass is not homogeneous and veins or striae exist, the reflected test diagram is seen to be blurred in patches or along the course of the vein (Fig. 3 *a*).

(14) *Astigmatism*. Astigmatism is indicated by the image being magnified or diminished more in one direction than in another at right angles to it and also by the lines appearing intensified in one direction and grey in the other, just as when viewed through a cylindrical lens. It is sometimes advantageous to rotate the mirror, when astigmatism is suspected, in order to bring the axis of the cylindrical surface parallel to one set of lines so that the effect may be more noticeable (Fig. 3 *b*).

(15) *Curvature*. The radius of curvature is determined by observing the amount

the mirror magnifies or minifies. Limiting circles (see paragraph (5)) are drawn on the test chart, of diameters controlled by the specified curvatures and the observing conditions of the test. The formula for calculating the diameters of the test circles is derived as follows:

In Fig. 4 let

$\frac{H}{2}$ = Semi diameter of mirror
$\frac{C}{2}$ = " " object (test circles)
$\frac{I}{2}$ = " " image
u = Distance of object
v = " image
d = " eye or telescope
R = Radius of curvature of mirror
a = Aperture of observing telescope

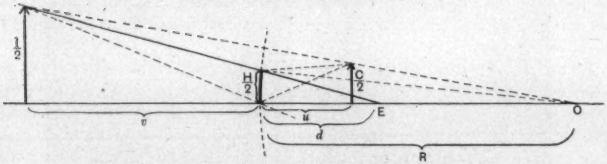


Fig. 4. Optical Conditions in Heliograph Mirror Testing.

From similar triangles

$$\frac{I}{H} = \frac{d+v}{d} \quad \text{and} \quad \frac{C}{I} = \frac{u}{v}.$$

Therefore

$$\frac{C}{H} = u\left(\frac{1}{v} + \frac{1}{d}\right)$$

and since the mirrors have all long radii of curvature, v will always be negative; hence by geometrical optics

$$-\frac{1}{v} + \frac{1}{u} = \frac{2}{R} \quad \text{and} \quad \frac{C}{H} = u\left(\frac{1}{d} + \frac{1}{u} - \frac{2}{R}\right).$$

If the test chart is at the same distance from the mirror as the point of observation, then

$$d = u,$$

and

$$\frac{C}{H} = 2\left(1 - \frac{d}{R}\right)$$

from which the diameter of the object or circles just large enough to fill the mirror of radius of curvature R (with due regard to sign) can be calculated, if the observing point is small like a pin hole.

If we use a telescope of aperture a for observing, then we shall see rather more of the test board; this addition is

$$a \times \text{magnification of the mirror,}$$

and since the mirror is nearly plane the formula may for all practical purposes be written

$$C = 2H\left(1 - \frac{d}{R}\right) + a.$$

(16) When testing the curvatures it is well to have a, the aperture of the telescope, small, say about 0·75 ins, because the image does not lie in the same plane as the mirror, and therefore, as focussing is done on the image, the periphery of the mirror which is used as a gauge appears out of focus if a large aperture is used. For general observation of the reflected squares an aperture of about 1·5 ins is suitable and when in doubt as to curvature the aperture may be cut down by means of an iris diaphragm in front of the object glass.

(17) It is obvious from the formula that, when the mirror is truly plane, $R = \infty$ and $C = 2H + a$, that is, the diameter of the test circle is twice the diameter of the mirror plus the diameter of objective of the observing telescope, and obviously this must be the case since the image in a flat mirror is exactly as far behind the mirror as the object is in front.

By the aid of the test diagram, knowing the diameter of the mirror under test, we can conversely determine the focal length of any mirror by noting the diametrical number of squares which can be seen in it—in effect the magnification of the mirror. This method seems very applicable to mirrors of long focal length and especially to the type of mirror silvered on the back where both refraction and reflection are involved.

(18) A comparison of the effectiveness of three different sizes of mirrors having the limits of curvature specified and also with plane surfaces is given below:

It can be shown that the divergence of the beam is given by the formula

$$\text{Divergence} = \left[\begin{array}{l}\text{Angle of incident rays}\\ \text{falling on the mirror}\end{array} + \begin{array}{l}\text{Angular aperture of the mirror,}\\ \text{i.e. angle subtended by mirror}\\ \text{at focal point}\end{array}\right]$$

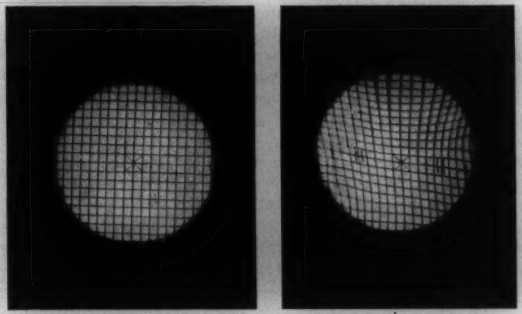
Approximately the point of divergence may be taken as the apex of the mirror, but in the case of concave mirrors it is some distance in front and in convex mirrors behind.

From the above the following table is calculated for reflections of the sun (diameter = 32′), and in the case of intensity the 5 inch mirror is taken as the standard.

	3 inch			5 inch			9 inch		
	Flat	$R = +500$ ft	$R = -1000$ ft	Flat	$R = +500$ ft	$R = -1000$ ft	Flat	$R = +500$ ft	$R = -1000$ ft
Spread at 6 miles	98 yds	109 yds	104 yds	98 yds	116 yds	107 yds	98 yds	130 yds	114 yds
Intensity of Beam at 6 miles	0·36	0·29	0·32	1	0·71	0·84	3·24	1·84	2·39
Angular Aperture of Mirror	—	3′ 26″	1′ 43″	—	5′ 44″	2′ 52″	—	10′ 19″	5′ 9″

It will be seen from the above table what an important effect curvature has upon the signals, both as regards spread and intensity, and the above figures relate only to normal incidence and reflection whereas defects of the mirror, in general, are magnified under ordinary conditions of signalling where incidence and reflection are never normal.

(19) *Effects of Frame.* Precaution should be taken to ensure that mirrors used for signalling are mounted so as to be free from flexure, which is readily caused by unequal pressure of the retaining ring or supports, thus causing distortion of the image. The glass should therefore be as thick as permissible and the mirror



a *b*

Fig. 5. (*a*) Mirror unmounted, (*b*) same mirror mounted and distorted by pressure in frame.

supported on three points with corresponding antagonising springs so that the mirror can "breathe." The effect of bad mounting is shown in Fig. 5. A mirror thus distorted would scatter the signals widely and not carry as far as it is capable of doing when properly supported and indeed an ordinary commercial mirror would be as effective.

(20) The photographs illustrating this paper were taken with a telephoto lens and, in order to diminish the exposure necessary to obtain a photograph in a reasonable time, a somewhat large aperture was used, so that they are not to be taken as applying in all respects to visual observations.

AN INTERFEROMETER FOR TESTING CAMERA LENSES

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MS. received, 25*th January*, 1921. *Read and discussed*, 14*th April*, 1921.

Abstract. The instrument is an application to camera lens testing of the principles of an earlier instrument described in the *Philosophical Magazine*, but it differs from the lens interferometer there described in that the camera lenses can be tested for oblique pencils. The instrument gives aberrations in the form of an interference picture (that can be photographed), which is a contour map of the aberrations of wave front expressed in wave lengths of light in comparison with the wave front of a perfect camera lens.

Interferometers for the testing and correction of prisms, and of lenses (for axial pencils), have been described by the author in the *Philosophical Magazine**, and in the patent specifications under which they are protected in this and foreign countries. The subject is also dealt with, and the principles of the camera lens interferometer outlined, in the 21st Traill Taylor Memorial Lecture†, where a number of photographs of the interference effects shown by camera lenses are given.

The object of the present paper is to give a detailed description of a Camera Lens Interferometer recently made for and despatched to an important optical firm by Adam Hilger, Ltd. It is intended that it should form the standard model of this instrument.

A very brief description, therefore, of the author's earlier interferometer for the testing and correction of prisms will suffice for the purpose of this paper.

The Prism Interferometer.

This instrument in its simplest form resembles the well-known Michelson interferometer, the main optical differences being that the two interfering beams of light are brought to a focus at the eye of the observer, that the incident light is collimated, and that the optical element to be tested is placed in one of the beams. It is shown in diagram (Fig. 1) as arranged for the correction of a 60° prism, such as is used for spectroscopy.

The light used must consist of a limited number of very homogeneous radiations. Such a light may be obtained from a Cooper-Hewitt mercury vapour lamp. The particular radiation for which it is desired to make a test is isolated by a suitable filter.

* *Phil. Mag.* 35 (Jan. 1918), 49.
† Printed in *The Photographic Journ.* Nov. 1918.

The light from the source is reflected by the adjustable mirror *A* through the condensing lens *B*, by means of which it is condensed on the aperture of the diaphragm *C*. The diverging beam of light is collimated by a lens *D*, and falls as a parallel beam on a plane parallel plate *K*, the second surface of which is silvered

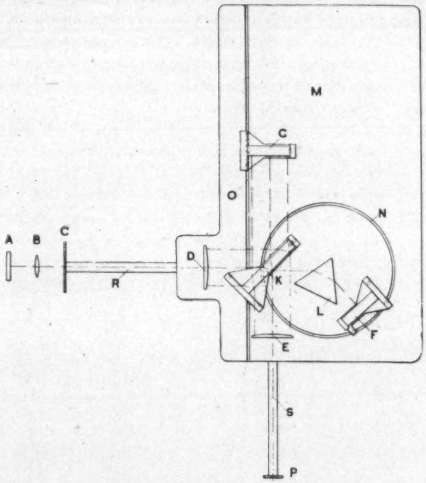


Fig. 1. Diagram of Prism Interferometer.

lightly so that a part of the light is transmitted and part reflected. The major part should be reflected. One part passes through the prism *L* in the same way as in actual use, and being reflected by the mirror *F* passes back through the prism to the plate *K*. The other part of the light is reflected to the mirror *G* and back again to the plate *K*. Here the separated beams recombine, and passing through the lens *E* each forms on the eye placed somewhat beyond the aperture in the diaphragm *P* an image of the hole in the diaphragm *C*.

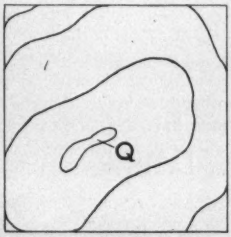


Fig. 2.

When the mirrors are adjusted, interference bands are seen which form a contour map of the glass requiring to be removed from the prism face in order to make its performance perfect. Fig. 2 represents in diagram a typical map, where *Q* represents the highest point of a "hill." The procedure in such a case is to mark

out the contour lines on the surface of the prism with a paint brush and then to polish first on the region Q, subsequently extending the area of polishing first partly, then wholly, to the next contour line; and so on. The marking out of the prism surface can be done while observing.

(At this point the author projected on the screen by means of a prism interferometer—using "white light" bands—the interference effects seen on locally heating a glass plate, letting a drop of warm water fall into cold water, putting a warm thermometer in cold water, etc. He also showed how, by putting in the interferometer a stack of glass plates all from the same melting, their very small differences of refractive index could be measured.)

In the lens interferometer all parts are left as in the prism instrument except that the mirror F (Fig. 1) is removed and replaced by the lens under test and a

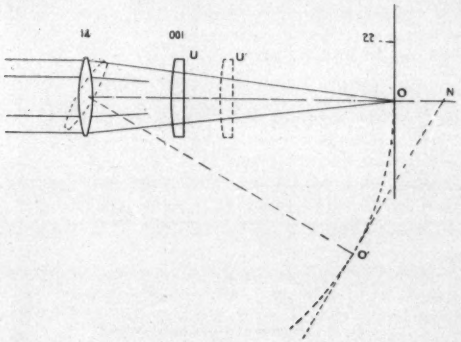


Fig. 3.

convex mirror, the latter being so disposed that its centre of curvature coincides with the focus of the lens. Under these circumstances a beam whose wave front is a plane perpendicular to the axis of the lens will, after passage through the lens, be reflected back on its own path by the convex mirror, and if the lens be free from spherical aberration the reflected beam will, on finally emerging from the lens, once more have a plane wave front. If it has not, then the departure from planeness will produce interference bands which form a contour map of the corrections which will have to be applied to the lens to make its performance perfect.

The Camera Lens Interferometer.

An apparatus which will test for axial pencils only is of course of little use for testing camera lenses. The modifications essential for the latter purpose are:

1. Means of rotating the lens about a line at right angles to the axis and passing through the second principal point.

2. Mechanism whereby, simultaneously with the above rotation of the lens, the convex back-reflecting mirror is automatically moved away from the lens in such a way that its centre of curvature always falls on the plane, perpendicular to the axis of the lens, on which the lens is desired to form its image.

Thus, in Fig. 3 the full lines represent the lens and mirror of the ordinary lens interferometer for axial pencils. The modifications necessary in the relative positions of lens and mirror for pencils oblique to the lens are shown by the broken lines. The mechanism must obviously be such that $UU' = ON$. Such, briefly, is the principle on which the camera lens interferometer is constructed.

Capacity of the Standard Camera Lens Interferometer.

The Camera Lens Interferometer to be described will test practically every camera lens of from 4″ (101 mm.) to 27″ (686 mm.) focal length. Lenses of 4″ (101 mm.) focal length can be tested for oblique pencils up to 50° on each side of the axis. The longest focal length which can be tested depends upon the angular range required on each side of the axis, and is as follows:

$32\frac{7}{8}$″	lenses can be tested up to an obliquity of				5°
$32\frac{1}{8}$″	,,	,,	,,	,,	10°
$31\frac{7}{8}$″	,,	,,	,,	,,	15°
31″	,,	,,	,,	,,	20°
$29\frac{7}{8}$″	,,	,,	,,	,,	25°
$28\frac{5}{8}$″	,,	,,	,,	,,	30°
27″	,,	,,	,,	,,	35°
$25\frac{3}{8}$″	,,	,,	,,	,,	40°
$23\frac{3}{8}$″	,,	,,	,,	,,	45°
$21\frac{1}{4}$″	,,	,,	,,	,,	50°

and shorter focal lengths up to at least 50°.

Flange. The lens holder is screwed to take the Royal Photographic Society's 6″ diameter thread. The maximum aperture which can be examined is $5\frac{1}{2}$″, and the largest lens mount which the holder will accommodate is 7″ maximum diameter.

Details of the Apparatus.

The annexed drawings show the apparatus:

Fig. 4, a general view.
Fig. 5, a plan.
Fig. 6, a side elevation.
Fig. 7, a side elevation of the mirror carriage.
Fig. 8, a side elevation of the mirror carriage and crossbar carriage.
Fig. 9, an end elevation of mirror carriage.
Fig. 10, plan of adjustment for crossbar carriage.

The rotation of the lens carriage is effected by means of a bar 105 (Fig. 6), parallel to the axis of the lens and extending to the outer edge of the interferometer A scale and index are provided so that the angle through which the axis of the lens is turned can be measured. Upon the bar and at right angles to it is mounted

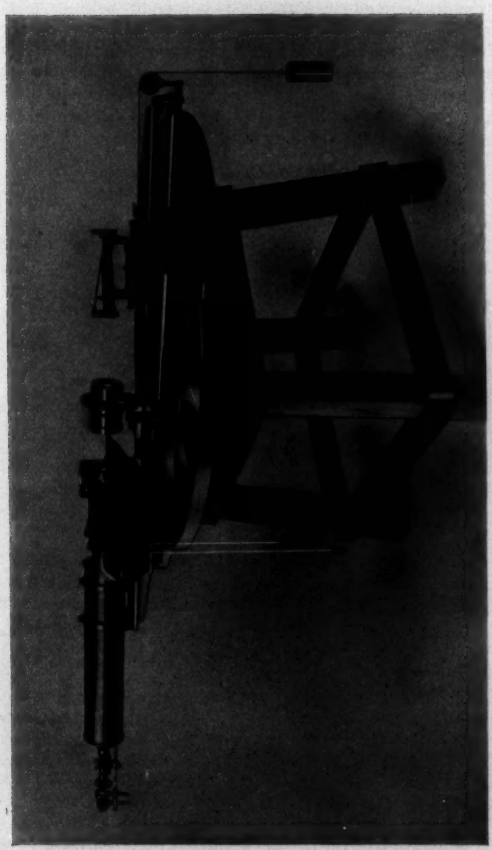
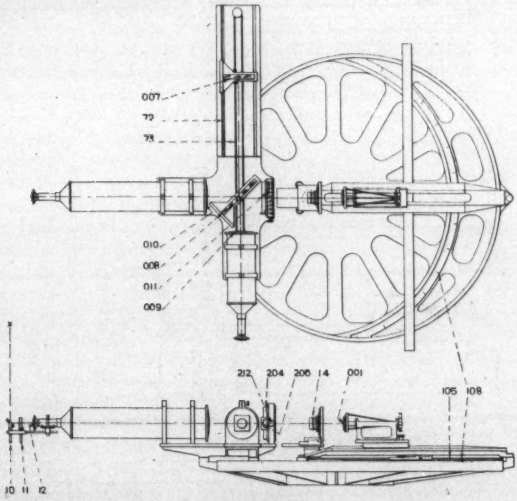


Fig. 4.

a crossbar 160 (Fig. 10), whose distance from the axis of rotation of the lens can be adjusted and measured by a scale engraved on the axial bar 105. The crossbar is clearly shown in Fig. 5, but not numbered. The convex mirror 001 (Fig. 6) by which the light is reflected back through the lens is adjustably mounted on a carriage and the carriage is automatically moved towards or away from the lens so that the centre of curvature of the mirror is always in the focal plane in which the lens is supposed to form its image. This is accomplished by a flexible connection being led from the carriage and over a pulley to a weight, and by there being upon the carriage a roller which is retained in contact with the crossbar above mentioned by the action of the weight.



Figs. 5 and 6.

Light from a suitable source is reflected by a mirror 10 (Fig. 6) and condensed by a lens 11 on to the aperture of a diaphragm 12, through which it passes. The diaphragm is so mounted that it can be readily interchanged with another of different aperture if desired. After passing through the aperture, the light is rendered parallel by a lens 010 (Fig. 5), and passes to a plane glass plate 008. The surface of the glass plate is partially silvered so that part of the light is reflected, and part transmitted by it. The transmitted light passes on through a pair of deflectors 011, by means of which the light can be deflected in a horizontal plane, the deflectors being rotated in opposite directions by the milled head 212 (Fig. 6). The deflection is measured by a scale on the drum 204 and index 206. The light passes

onwards to the lens 14 which is under test and to a spherical mirror 001, by which it is reflected back through the lens under test and the deflectors 011 (Fig. 5) to the plate 008 and is partly reflected to the lens 009 by which an image of the aperture in diaphragm 12 is formed. The part of the beam which is reflected by the plate

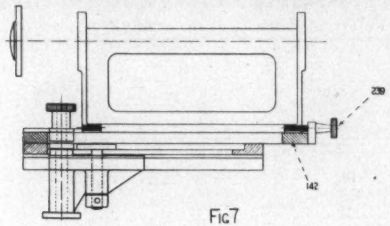


FIG 7

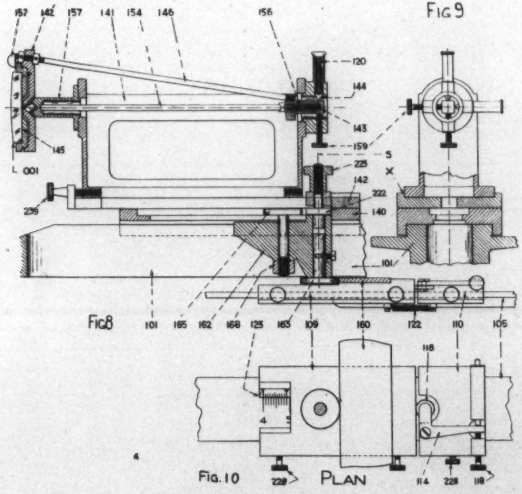


FIG 9

Figs. 7, 8, 9 and 10.

008 proceeds to the mirror 007, by which it is reflected back again. A part is transmitted by the plate 008, and combines with the beam returning through the lens 14.

The lens under test is mounted on a cross slide whereby it can be adjusted either along or at right angles to its optical axis, and in this way its second principal

point can be brought on to the axis about which it is rotated by the bar 105 (Figs. 6 and 10). The spherical back reflecting mirror 001 is mounted in a cell 145 (Fig. 8), which fits the adapter 142′ and is clamped by the turn buttons 152. Cells, each containing a mirror of different radius, are thus readily interchangeable.

The adapter 142′ is pivoted on a ball resting in a coned recess and is kept in contact with it by the spring 156 and three rods, of which two 146 and 154 are shown. The spring box 143 to which one end of the rod 146 is attached, also forms the end of a lever against which the horizontal and vertical slow-motion screws 159 (Figs. 8 and 9) and spring plungers 144 act. The centre of curvature of the mirror can thus be adjusted in a horizontal and a vertical plane.

The mirror pivot bearing 157 and slow motion are mounted on a frame 141, adjustable on the plate 142 by the screw and milled head 239 (Fig. 7) along the optical axis. A pivot 222 (Fig. 8) slides in a slot and can be clamped to the plate 142 in any desired position by the clamp 223. The pivot works in a bearing 162, which is also the bearing for the roller 163. The plate 142 rests on the carriage 140, on the under side of which the bearing 162 is clamped by the bolt 165 and nut 166. A long slot enables the bearing 162 with the roller 163 to be clamped in any position on the carriage.

These adjustments enable the centre of curvature of the mirror to be brought exactly on the axis of the roller and on the optical axis of the lens under test. The roller 163 is maintained in contact with the crossbar 160 by means of a flexible connection to a weight (not shown on the drawings). The carriage 140 slides parallel to the optical axis on the ridged bed 101; thus when the lens 14 is rotated by the crossbar 160, the roller keeping contact with the crossbar automatically shifts the carriage in such a way that the mirror centre of curvature is always in the plane in which it is desired that the lens should focus its image. The vernier 123 (Fig. 10) measures the distance from the centre of the roller in the axial position to the axis of rotation of the lens; thus when all adjustments have been made this vernier gives the focal length of the lens to an accuracy of about 0·001 inch. In Fig. 3 the lens 14 and mirror 001, with focal plane 22, are shown in full lines, and the corresponding position for an oblique pencil in dotted lines.

The mirror 007 (Fig. 5) is mounted on a carriage moving on grooves 72, and actuated by means of cords 73. 009 is a lens through which the recombined beams from the mirrors 007 and 001 pass, being thereby converged on to the observer's eye.

Adjustment of the Apparatus, and setting up a lens for test.

It will be sufficiently obvious to members of this Society, accustomed as they are to make or use optical instruments, that the geometrical conditions implied in the above description must be attained with considerable accuracy if the apparatus is to form a reliable test of performance of a camera lens. Furthermore, it must be possible to perform all the necessary adjustments preliminary to a test in a simple, systematic, and speedy manner if the apparatus is to form a useful tool in connection with the manufacture of camera lenses. A routine has been worked out

whereby an observer can satisfy himself that the geometric conditions are successfully fulfilled, and a systematic method of setting the lens and apparatus has been devised, enabling a lens to be mounted on the apparatus and completely tested for five or six obliquities within a quarter of an hour.

Not to waste space in detail which is not of very general interest the nature of the adjustments requiring to be made with accuracy will alone be given here.

(*a*) The surface of the lens mount, against which the flange of the camera lens screws, must be parallel to the working edge of the crossbar.

(*b*) The axis of the collimator must be parallel to the ways 101 (Figs. 8 and 9), which bear the mirror carriage.

(*c*) The mirrors 007 and 008 (Fig. 5) must be so set that the beam of light from the collimator reflected from 008 to 007, and back again, will form an image of the aperture in diaphragm 12 (Fig. 6) on that aperture itself.

(*d*) The convex mirror must have its centre of curvature on the axis *S* (Fig. 8) of the roller.

(*e*) The camera lens under test must have its second nodal point on its axis of rotation.

(*f*) The centre of curvature of the convex mirror must coincide with the focus of the lens under test.

Observation of the Aberrations.

The apparatus measures the degree to which the wave front, impressed by the lens on light from a distant point source, differs from a spherical wave front. The indications are given in aberrations of wave front to a scale of wave lengths, the aberration shown being in every case twice that present in the once transmitted beam which normally forms the image of a distant point. The form in which the indications are presented is that of a series of interference fringes which are lines of equal aberration of wave front. Otherwise expressed, the interference fringes form a contour map of the wave front with reference to a sphere.

The aberrations of a centred optical system are, chromatic aberration apart, of the following forms:

Spherical aberration in axis,
Coma,
Astigmatism,
Curvature of image,
Distortion,

and are characterised as follows, quoting E. T. Whittaker*.

(*a*) *Spherical aberration.*

"The marginal rays, or rays which pass through the outer zones of the lens, do not meet the axis in the same point as the paraxial rays."

(*b*) *Coma.*

"The linear magnification of a very small object, situated on the axis of the instrument, is different when different zones of the instrument are used to form

* *The Theory of Optical Instruments.* Cambridge Univ. Press, 1907.

the image." Obviously only a small angular field is here considered: however, in the case of photographic lenses, highly corrected as they are over large angular fields, essentially the same definition obtains.

(*c*) *Astigmatism.*

"A thin pencil which is not homocentric but diverges from (or converges to) two focal lines is said to be astigmatic." Here, similarly, one has in the case of photographic lenses to deal with image-forming beams of large angular extent.

(*d*) *Curvature of Field.*

"In order that a plane object may give a plane image the condition for flatness of field must be satisfied." Otherwise the focal surface is said to have curvature.

(*e*) *Distortion.*

"The image is said to be affected by distortion when the object (supposed to be a plane figure at right angles to the axis of the lens) gives rise to an image which is not geometrically similar to itself."

This classification of aberrations, established by the mathematical investigations of von Seidel, Petzval, Abbe, and Helmholtz, finds complete acceptance with practical opticians. That such should be the case is a little surprising, for all these investigations have been carried out on the assumption that terms of orders higher than the third in the angular aperture and field of view are negligible*—an assumption which is certainly not justifiable in the case of camera lenses. Furthermore, they have, of course, been arrived at by the methods of geometrical optics, and on that account break down entirely in cases where one is concerned with details of definition approaching the ideal resolving power of an optical system.

Nevertheless, it seems that, broadly speaking, all observed aberrations may be grouped for descriptive purposes in this way. For this reason we give in Fig. 11 reproductions of sketches of the interference appearances corresponding to fairly pure examples of these five aberrations. A short consideration of this figure will readily enable the observer to state on inspection the aberrations of the lens he has under test in terms of wave length and to recognise the outstanding characteristic in any particular case.

To make a rapid translation of these interferometer pictures into the terms of geometrical optics requires a little practice. But an observer, bearing in mind that these pictures are contour maps of wave surfaces, and working continuously for a few days with such an interferometer, will at the end of that time be able almost without thought to form a mental picture of the focus corresponding to the interference pattern.

If a quantitative statement of the aberrations is required in terms of ordinary geometrical optics, we can proceed in several ways. If the aberrations of wave front amount to three or four wave lengths or more, as in the case of existing camera lenses they always do, one may count or estimate the bands per inch at whatever

* It is true that the sine condition has been derived by Clausius and Helmholtz from more general considerations, based on the laws of thermodynamics; but we are here concerned, not with the conditions necessary to secure freedom from aberrations, but with the nature of the defects of the image resulting from non-compliance with those conditions.

Fig. 11. Wave front sections after single passage through lens.

point of the lens we desire to find the direction of the ray through it, which immediately gives us the angular aberration; or we may make use of the deflectors described below. For this latter method one requires not only to be able to rotate the deflectors relatively to each other in opposite directions as is provided for in the standard instrument, but also to rotate the pair together. In this way one can impose on the incident wave front a deviation of any desired amount in any desired direction. We can under these circumstances broaden out the bands at any point of the lens for which we require to find the aberration according to geometrical optics. This operation amounts in effect to fitting our reference sphere to various points of the wave surface given by the lens, and is immediately translatable into the desired terms.

If the aberration of wave front amounts, however, only to one or two bands or less, the nomenclature and methods of geometrical optics break down entirely, at any rate from the point of view of affording us any idea of the distribution of light in the neighbourhood of the focus of the lens. We must then use the methods of the wave theory of light. The question has been mathematically treated by various investigators who have, of course, all assumed as available in the form of a mathematical expression (or have calculated for various specific cases) the aberration of wave front. For instance, to take a recent example, Dr Silberstein* determined the light distribution round the focus of a lens having aberration, first obtaining an expression for the aberration of wave front, and then using it to determine the distribution of light intensity.

So far as the author is aware, no one has yet attempted to determine the distribution of light intensity around the focus of an existing lens from experimental data obtained from the lens itself. The following method would appear to be practical, and to afford results accurate to a fair degree of approximation. It is an application of the method of Cornu's spiral. Fig. 12 represents an interferogram as seen on one of the lens interferometers described, the thick lines representing dark bands. All these interferograms may, of course, be considered as maps, showing the relative phase in which the disturbance passing through various parts of the lens reaches the surface or the centre of the reference sphere. I have marked one of the dark bands 0. The next dark band will therefore be correctly marked $0{\cdot}5\,\pi$, since we are considering single passage through the lens only, while the interferogram is obtained by double transmission. Having obtained a photograph of this appearance one enlarges it to such a convenient size that a number of fractional phase lines can be interpolated, as has been done by the lines of medium thickness marked 0, 0·1, 0·2, 0·3, etc. Finer lines again have been drawn intermediately to the others.

Now let us consider the successive strips of the lens corresponding to the regions bounded by these finest lines. The light passing through the first complete strip may be considered to have the phase 0, the second strip the phase 0·1, the third

* "Light Distribution round the Focus of a Lens at various Apertures," L. Silberstein, *Phil. Mag.* 35 (Jan. 1918). The paper gives a brief résumé of earlier work in this direction. See also the interesting paper by Conrady on Star Discs (Monthly Notices, *R.A.S.*, June, 1919), as a further example of the more recent work.

strip the phase 0·2, and so on. The total disturbance at the centre of the reference sphere, provided the wave front travelled on, can be approximately found in the following way. The enlarged photograph is cut into strips along the finest lines. Each strip is weighed, and a drawing (Fig. 13) made in which the weights of the strips are vectorially added, the direction of each vector being that indicated by the phase relationship. The amplitude of the resultant disturbance will, of course, be represented by the resultant vector OM, and the relative intensity of illumination at that point by the scalar square of this vector.

One can carry this process out with a much greater speed than the corresponding mathematical calculation, even assuming we can easily express the shape of wave

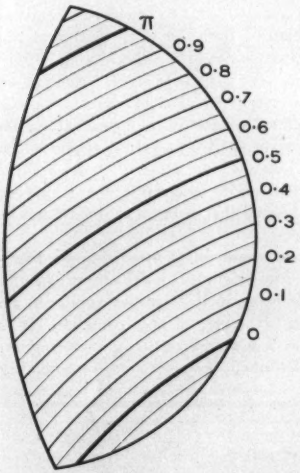


Fig. 12.

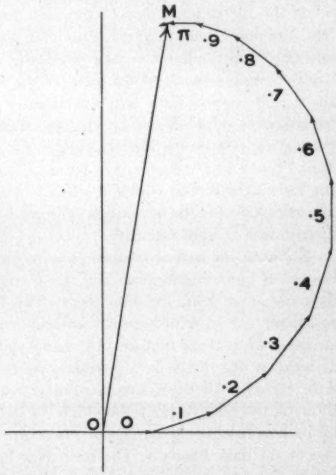


Fig. 13.

front obtained experimentally in a convenient mathematical form, and by working from point to point by means of the deflector system the intensity distribution in the focal region can be completely explored.

It is necessary in the design of photographic lenses to consider the above aberrations and their effect as a whole upon the focus: for obviously it is futile to design a lens that produces images showing an absolute freedom from one particular type of aberration, if other aberrations are present to such a degree as to render the lens useless. It therefore follows that the residual aberrations must be so adjusted that the focus, although affected by minute quantities of aberration, does not betray the presence of any one aberration to an extent that is likely seriously

to interfere with the efficient performance of the lens; and herein the ability of the designer manifests itself. This done, there can be no better verification or criticism of the design of a photographic lens than that yielded by a thorough test on the Camera Lens Interferometer, since the extent of the departure from sphericity over the whole of the emerging wave front may be at once observed and recorded. The indications are given in terms of the only satisfactory criterion of good definition which has yet been put forward, namely, freedom from aberrations of wave front.

In favourable cases correction by retouching can be carried out quite independently of any knowledge of optical theory, or of the mode of design of the lens.

There is only one of the aberrations that requires a further special mention—that is DISTORTION. It is in order to measure distortion that the deflector mount 204 (Fig. 6) has been added to the apparatus. Distortion may be considered as the formation of an image of one point in the object plane in a position which, according to the ideal optical collineation, should be occupied by the image of some other point. Obviously, by symmetry, such distortion is always radial—that is, on any line drawn from the point of the photographic plate outwards from

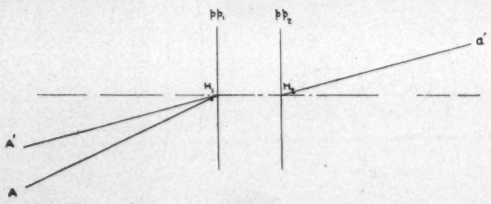


Fig. 14.

the axis of the lens, a point image which should be formed at a is formed at some other point on that line a', see Fig. 14. If a' is the image of A, while A' is the object point corresponding to a' by Gauss construction, then the angle AH_1A', if known, affords a measurement of the distortion at this obliquity. This angle is in effect measured by the deflector system. Let us suppose with a particular lens, at obliquity U, the pencil of rays is, after passage through the lens, deviated so as to cause distortion. Let us then impress on the incident beam, by means of the deflector system, a known deviation ΔU, such that the pencil of rays is once more brought central with the centre of curvature of the convex mirror (which centre represents the point of the image plane for which the performance of the lens is for the time being under test). Then the distortion of the lens for that obliquity is given by

$$\frac{\tan(U+\Delta U)}{\tan U} - 1 = \frac{0.000\,5818\,\Delta U}{\sin 2U},$$

the magnification in the neighbourhood of the axis being taken as unity. The graduation gives the angular rotation of each deflector, and ΔU can be found from the tables supplied with each instrument.

Visibility of the Bands.

Valuable information relative to the bands of the prism interferometer will be found in a paper by Guild*. There is so far no published information relative to the visibility of the bands given by these lens interferometers. The following remarks may be found useful in this respect. If instead of a small aperture in the diaphragm 12 (Fig. 6) an extended light source be used, then it will be found that, the instrument having been adjusted with a good lens, and observation being made with an eyepiece in the telescope, a series of concentric rings will be observed (Fig. 15). These are due to the variations of relative retardation of the interferometer beams due to the rays in the lens beam traversing a longer or shorter path according to their inclination. Of the ring system so observed it must be noted that each point of it is contributed to by every part of the camera lens. Such a ring system is also in general observable in the case of a camera lens which has aberrations; and it is in this case also true that every part of the camera lens participates in the formation of every point of the ring system observed in the eyepiece. In Fig. 15 are shown side by side a diagram illustrating the ring system observed in the eyepiece, and the interference bands for a particular photographic lens.

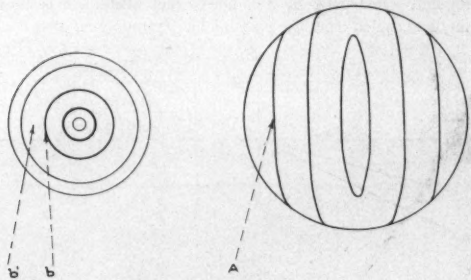


Fig. 15.

Let us suppose the eye of the observer receives light firstly only from a point b and secondly only from a point b', and let us direct attention to a point of the lens A. Then if, when light reaches the eye through the point b, the point A on the lens appears bright, the same point on the lens will appear dark when the light reaches the eye through the point b'. It is thus obvious that, unless the light reaching the eye is obtained from a region which is small compared with the breadth of a single ring as seen in the eyepiece, the interference appearances seen on the camera lens will be faint. Obviously, then, to secure good visibility the light which reaches the eye of the observer should come from the centre of this ring system. In the adjustments described above this point has been carefully attended to.

* *Proc. Phys. Soc.* 33 (1920), 32, 40.

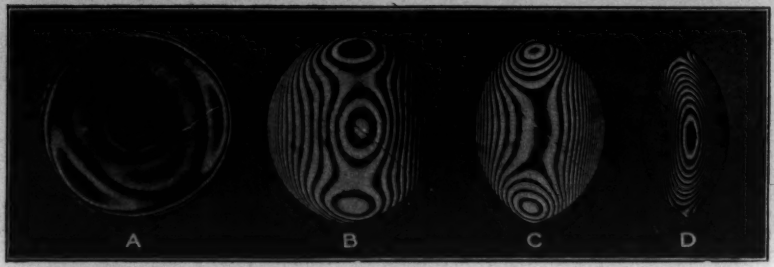


Fig. 16.

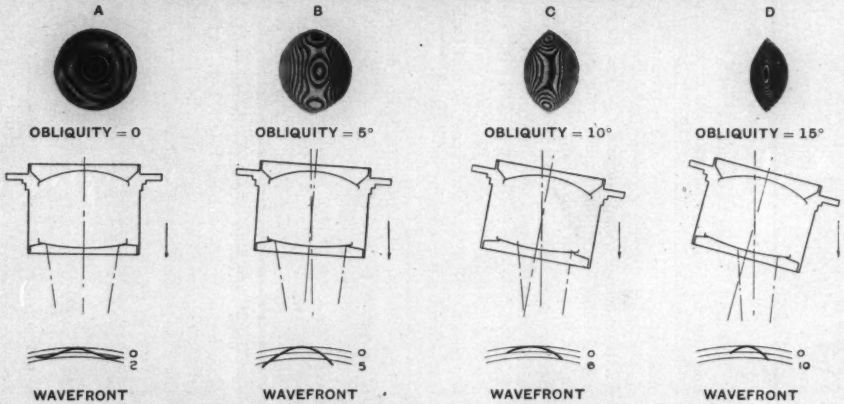


Fig. 17. Repetition of Fig. 16, showing tilt of lens, and wave fronts after single passage through lens.

It is desirable that the ring system should be as large as convenient in order that the amount of light admitted to the apparatus, and eventually to the eye, may be as great as possible, without making the bands indistinct. The closer the convex mirror is to the camera lens, the more nearly is this condition fulfilled. For this reason a range of mirrors is provided which enables, for any lens, a mirror to be chosen which will give ample illumination for observation.

Photography of the Appearances.

The first difficulty in connection with the photography of the appearances is that with the changing temperature of air and apparatus there is a slow movement of the interference bands. Although this is in no way detrimental to ordinary observation, since in spite of this movement the bands retain their same general shape, yet, during the exposure necessary for photography of the bands, their gradual movement may produce a general fogging of the plate. For this reason it is desirable when photographing the appearances to use a silica tube mercury vapour lamp. With such a lamp photographs can readily be obtained, either for green or violet radiation, with a 2-minute exposure. With a suitable camera, therefore, in which five exposures can be given successively on one long plate a complete photographic record can be obtained of the performance of any camera lens in a very short time. For example, if the observer be given for test a photographic lens he can within one hour hand the lens back with a record and photographic plate affording the following information.

(*a*) Focal lengths of the lens correct to 0·″001 for the green and violet rays.

(*b*) Complete aberrations (including distortion, and the chromatic variations of aberration) for axial pencils and for five obliquities.

Figs. 16 and 17 show photographic reproductions of the interferograms of a well-known lens of high repute for the mercury radiation (546$\mu\mu$) for the axial beam and for obliquities of 5, 10, and 15 degrees. It will be seen that even the best photographic lenses—of which this is a fair example—are very far indeed from perfection.

I must not fail to record my thanks to Mr Dowell and Mr Perry, members of the technical staff of Adam Hilger, Ltd. To the former is due the detailed design of this Interferometer, while the latter has carried out all the adjustments, and taken the photographs reproduced in Figs. 16 and 17. To Mr Green, chief optical foreman of the firm, is due, on this as on other occasions, recognition of his skill, patience, and never failing fertility of ideas.

DISCUSSION

Mr J. Guild said that some misapprehension appeared to exist among opticians as to the proper function of interferometer methods and the nature of the claims made for them. Their advantage did not lie so much in increased sensitiveness as compared with older methods but in the completeness of the information given. He had recently had it demonstrated to him that in the case of telescope lenses, for instance, any lens which would show imperfection on the interferometer would be

classed as imperfect by an observer skilled in the use of the star test; but the interferometer gives complete information both as to the nature of the defect and how it can most easily be remedied. Similarly diffraction gratings could be examined on interferometers of this type. Here again the interferometer will not show defects which are too slight to be appreciated in the ordinary use of the instrument, but it reveals at a glance the whole character of the diffracted wave front and gives complete information about the behaviour of the ruling engine at each part of the grating surface—information which, by the old methods of test, can only be deduced from very prolonged and tedious tests.

Coming to the instrument described in the paper he would like to know whether from the nature of the interference patterns for oblique pencils it would be possible by retouching to improve more than one outstanding aberration.

As regards the adjustment for best visibility he thought he had made it plain in his paper, to which Mr Twyman had referred, that the considerations there given applied to lenses as well as to prisms and plates. A lens is simply made up of a number of elementary prisms of different angles distributed round the optic axis. The general condition for best visibility in all cases is that the light should be normal to the "film" to which the arrangement is optically equivalent. This is attained in practice by adjusting the plane comparison mirror so that the light reflected from it is refocussed on the pinhole of the collimator. Mr Twyman's explanation from first principles was nevertheless interesting and useful.

Mr J. Rheinberg said that if any distortion is impressed on the wave front by a local defect the distorted portion of the beam would go back through a different portion of the lens, and he would be glad to learn how this might affect the general problem.

He further asked whether a retouching of a lens for paraxial rays was likely to improve or deteriorate results as regards oblique rays.

Prof. F. J. Cheshire said that in the very early days of the war he was successful in persuading the author to bring out his first interferometer in national interests. He was disappointed that so little interest had been aroused in this new invention. There was a distinct danger that the benefits to be derived from it would be captured by foreign countries.

He would like to ask in what respect the lens which gave the results illustrated in Fig. 16 could be corrected, and what would be the ideal succession of patterns as the obliquity was increased. Dennis Taylor has referred to the inevitable astigmatism even at $\frac{1}{2}^\circ$ off the axis.

Mr L. C. Martin was not quite sure whether a set of convex mirrors could be made of sufficient accuracy for the purpose.

He approved of the instrument for tests on camera lenses rather than for the final testing of astrographic objectives, etc.

Distortion of wave form due to aberration was dealt with in a paper by Prof. Conrady (Monthly Notices, *R.A.S.*, June, 1919). With regard to the use of aspherical surfaces another paper by the same author (*Ibid.* Jan. 1920) has shown that except in dealing with spherical aberration similar aberrations and the consequent difficulties would arise even with aspherical surfaces, and this tended to

destroy the hope that a perfect optical system could thus be produced in any unexpectedly advantageous manner.

Mr T. Smith suggested that two distinct centres of rotation should be provided, relatively adjustable in separation. Thus even a telephoto lens (which might be fixed) could be tested over the whole field of view by rotating the interferometer proper about an axis through the centre of the entrance pupil and moving the mirror by means of the nodal slide about the nodal point.

With regard to the visibility of the fringes he would like to refer the author to the quartz mercury vapour lamp recently designed by Mr Guild (*Proc. Phys. Soc.* 32 (1920), 341) for interferometry.

He agreed with the author's remarks about the standard of camera lenses. It is deplorably poor for exacting scientific work, chiefly due perhaps to no serious attempt having been made in the way of improvement. It would be possible to improve the standard if the difficulties of grinding and polishing aspherical surfaces were overcome. With such surfaces the corrections of the aberrations of a camera lens would be much more easily realised.

He strongly supported Prof. Cheshire's recommendation that it behoved them all to give this invention very serious attention. The author had provided a new tool, the ultimate value of which no one could now estimate. If proper use were made of it and the resulting problems were efficiently tackled, great improvement of camera lenses should follow.

Dr J. S. Anderson asked the author if he employed any direct method of testing the uniformity of curvature of the convex mirrors.

Mr G. E. Brown said that the instrument was of little interest to the average user of camera lenses, but was no doubt of great importance to manufacturers. Although camera lenses were far from perfect, they were quite good enough for the ordinary photographer. Before condemning camera lenses one should turn one's attention to the faults in cameras.

Mr R. S. Whipple thought that the introduction of any new tool, such as the one which the author had invented, opened up new fields of work, some of which were quite unconnected with the original work for which it was designed. He instanced the fact that the development of the large quarter-wave plates of mica by the late Prof. Silvanus Thomson as a means of obtaining circularly polarised light has brought into use a new method of studying the design of structures. A model of the proposed structure is made in celluloid and the stresses in it when under test can be determined from the colour effects.

The author, in reply, said he entirely agreed with Mr Guild in his statement as to the proper function of interferometer methods.

As to Mr Guild's query whether from the nature of the interference patterns for oblique pencils it would be possible by retouching to improve more than one outstanding aberration, the answer is "yes," provided the aberrations are of favourable sign and kind; and in at least one lens examined by the author aberrations favourable for correction were present.

He regretted that he had failed to realise that the general conditions of visibility of the bands in lens interferometry had been stated in Mr Guild's paper.

In reply to Mr Rheinberg, he admitted that the path of the beam on returning through the lens is different from its path on first passage through it. For all aberrations of interest, however, no error or ambiguity arose from this source, since the points on the lens surface traversed by the go and the return rays were extremely near together, and could not in fact be distinguished as separate by the eye of the observer, except in cases of aberrations too great to be suitable for investigation on this instrument.

If a lens were retouched to correct for axial rays, the effect on oblique rays can be simply calculated from a knowledge of the obliquity and the refractive index of the portion of the lens to which the correction was applied. The correction would, of course, be applied to that portion of the wave front which passes through the retouched portion of the lens, and this also, of course, can be readily found from the known obliquity.

To Prof. Cheshire the author desired to express his best thanks for valuable advice and encouragement in the early stages of developing these interferometers.

In reply to Prof. Cheshire's question he hoped at a later date to give photographs showing the extent to which successive retouching of a lens from its commercial form could improve it, and to show the interferograms corresponding to the successive stages of retouching.

The author agreed with Mr Martin that the making of a set of convex mirrors of sufficient accuracy was one of the prime difficulties in manufacturing an apparatus to deal with optical elements which approached ideal resolving power. He pointed out, however, in reply to Mr Martin and also to Dr Anderson's query, that with the instrument described a means of checking the accuracy of the convex mirrors was provided, in that the convex mirror was susceptible of rotation about its centre.

He thanked Mr Martin for referring him to the papers by Prof. Conrady in the *R.A.S.*, and hoped that he might be permitted to insert in his paper, as a consequence of Mr Martin's remark, a reference to Prof. Conrady's paper.

Concerning Mr Smith's remarks, the author desired to express his best thanks for a most valuable suggestion, and expressed his intention of endeavouring to apply Mr Smith's proposal if it were possible to do so with sufficient mechanical accuracy.

With regard to the testing of telephoto lenses, these can be dealt with by increasing the diameter of the convex reflecting mirror.

He was glad to note the introduction by Mr Guild of the modified quartz mercury vapour lamp, and would be very glad indeed to learn when such lamps might be obtained commercially.

The author agreed with Mr Brown that camera lenses were probably quite good enough for the ordinary photographer; in fact, for many photographers they were unnecessarily, and even for some artistic photographers, undesirably good; but there were many technical purposes for which better camera lenses were essential than are now available.

NOTE ON A HANDY FORM OF MEASURING MICROSCOPE

By T. F. CONNOLLY, M.Sc.

MS. received, 9th February, 1921. *Read and discussed, 10th March*, 1921.

Abstract. The instrument comprises a microscope system of relatively low power; a double image prism traverses the object space, and is controlled by the rotation of a milled band operating a spiral slot. Exit pupil discs of telescopes or other optical instruments and Brinell impressions can be measured by a single contact setting of the edges of the duplicated discs. The range in the experimental instrument is from 1 to 6 mm., and the accuracy when used with a fixed focus for Brinell impressions is about ± 0·02 mm. The reading scale is very open and is divided to 0·1 mm. No vernier is used.

Measurement of exit pupil to determine magnification.

In connection with the task of finding the magnifying power of optical instruments a usual and adequate procedure is to measure the diameter of the circle of light at the eyepiece of an adjusted instrument. This circle is the exit pupil of the optical system, often called the Ramsden disc. The ratio of the diameter of this disc to that of the entrance pupil, usually represented with sufficient accuracy by the aperture of the object glass, gives the magnifying power. The powers for various zones can be obtained by using suitable cover stops for the object glass and making similar measurements of exit and entrance pupils.

The Dynameter compared with the present instrument.

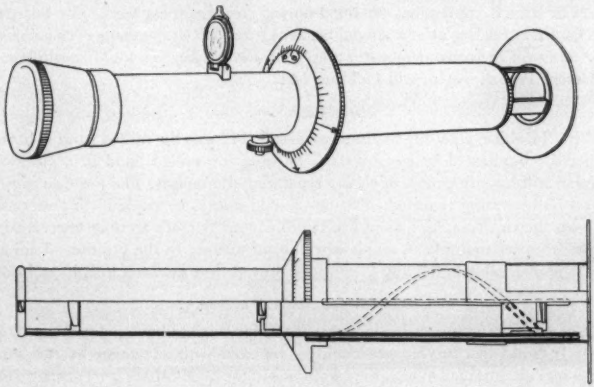
The usual workshop tool for taking such measurements is generally known as a dynameter. It consists usually of a microscope optical system having a ruled graticule or a line of serrations in the eyepiece. The measurement is made by counting the number of divisions or of teeth covered by the Ramsden disc as viewed through the eyepiece.

The present instrument is offered as a workshop tool improved in several respects over the normal type of dynameter. The most important advantage is that the reading is directly made after a single contact setting. The difficulty of holding an instrument steady, under the usual conditions of use, while a double reading or counting takes place is well known and is here practically eliminated. The optical elements used in the construction are highly corrected so that the optical results meet probable requirements. The mechanical design and construction is intended to secure accuracy to a relatively high limit together with convenience in use.

Description of the instrument.

The optical system of the instrument shown in the diagram (Fig. 1) consists of normal microscope components. The object glass, achromatic, has a numerical aperture (N.A.) of 0·08 and a focal length of 1⅝ inches (42 mm.). The eyepiece is of the Kellner type with a focal length of 18 mm. The objective is used at a "working distance" of about 3 inches and an "optical tube length" of about the same value. The initial magnification is therefore unity. The total magnification (× 12) is due to the eyepiece which is fixed in position and not adjustable for focus.

Traversing the whole of the space between the object being measured and the first lens is a biprism whose function it is to duplicate the image of the object with a variable separation depending on the position of the biprism in the tube. The



Figs. 1 and 2.

angles of this prism (about 4°) have been arranged so that edge contact setting on duplicated discs can be made for sizes varying from less than 1 mm. up to 6 mm. The prism is screwed into a sliding cage which is controlled by a pin passing from it through a straight slot and then engaging with a spiral slot which latter turns solid with the graduated knurled ring by which the setting is made (Fig. 2). The overall length of the instrument is 8 inches.

Range and reading of scale.

The scale of the instrument is divided to read to 0·1 mm. with a range of 6 mm. The divisions are intended to be subdivided by estimation giving as a unit reading 0·01 mm. (1/2500 inch). It would be easy to supply a vernier but its use for such subdivision is considered cumbersome and needless. This fact was pointed out to

me by Commander Baker who exemplified it by test readings of a sextant by estimation checked by a vernier dividing the interval into 30 parts. After very little practice accuracy in the estimation to 1 part can be obtained with ease. The conditions in such estimations are that the division lines are fine and well seen and that the interval to be divided subtends at the eye a sufficient angle to secure comfortable work. It may be roughly taken that, with a visual acuity represented by one minute of arc, division into 30 parts demands a minimum angle at the eye of half a degree. It adds to the ease of observation if this is increased to one or two degrees. A small reading lens (Fig. 1) has been added to the present instrument so that this condition is amply fulfilled.

Measurement of Brinell impressions.

A further important use for the instrument is in the measurement of the diameters of Brinell impressions obtained during steel hardness tests. For this purpose its direct reading after a single contact setting is an advantage over a charmingly designed instrument recently placed on the market for such measurements by Messrs Taylor, Taylor and Hobson, Ltd.

Method of use.

With the object carefully focussed or already in focus the milled band is turned so that the duplicated images overlap. Turning the milled band in a clockwise direction will have the effect of slowly separating the images. The position of final contact is the setting required. Settings should always be made in this way as it has been shown that setting from overlap to contact is more accurate than making contact from separation*. A single direction of turning to the position of adjustment is also of value in tending to eliminate loss of time between the pin and slots.

Conditions and limits of accuracy.

In connection with possible inaccuracies of focus it has been pointed out to me by Mr J. Guild that the biprism could be replaced with advantage by two small prisms set side by side. Where the conditions in the object space are constant such prisms would be an improvement as the apparent size of the image or contacts in the estimated focal plane would not vary for small errors in focal setting. The paths of rays through an object glass for biprism and side by side prisms are shown in Figs. 3 and 4. It will be seen that the *mean rays* of image forming bundles from the two halves of the object glass form an angle in a plane containing the line of measurement in one case while in the other they are in a plane at right angles to it†. A Wollaston quartz prism possesses some advantages over either form and it is hoped to use it in a future instrument.

Measuring images in air.

When measuring exit pupils or other aerial images, focussing is necessary and great attention should be given to it if considerable accuracy is required. A well

* Baker and Bryan, "Errors of Observation," *Proc. Optical Convention*, vol. II (1912).
† "Note on the Use of the Auto-Collimating Telescope in the Measurement of Angles," by J. Guild, *Proc. Phys. Soc.* 28 (1916), 242.

marked graticule is provided to indicate the correct plane and to serve as a standard of quality of image in focus and as a parallax reference plane. Dependent on the closeness of focus the resulting measurements approach the accuracy set out below.

Measuring Brinell impressions.

When used with a fixed focus, as for the measurement of Brinell impressions, the instrument is in its most accurate and satisfactory form. Consistent and accurate readings on rulings or discs can be made to within ± ·02 mm. in the actual experimental instrument.

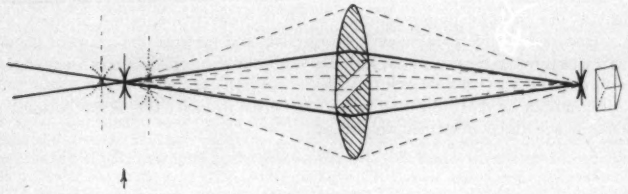


Fig. 3.

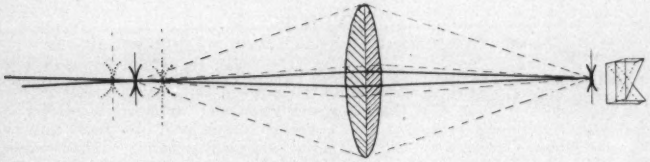


Fig. 4.

It is hoped in the near future to make an instrument for Brinell impressions only when the solidity and convenience of manipulation can be improved and the accuracy increased to within ± ·01 mm. throughout the range. This can be achieved by minor changes, both optical and mechanical, without increase of weight or size.

DISCUSSION

Instructor-Commander T. Y. Baker said that he had investigated the accuracy with which one could estimate fractions of a scale division and had found that, if a division was magnified so as to subtend about 2° at the eye, the error in estimation of any given fraction was no greater than 1/50 in the case of trained observers. He considered that in such cases the provision of a vernier was indefensible.

Prof. H. N. Russell referred to a paper by Albrecht, who found extraordinary differences in such estimations; some people were much more accurate when estimating near the middle of a division, and *vice versa*. All observers were found to improve with training.

Mr W. Shackleton mentioned that in one of the early Ramsden dynameters a split objective was used giving a double image as in Mr Connolly's instrument. From actual use of a dynameter of this form he had come to the conclusion that it was not more accurate than the usual direct reading instrument; at the same time it must be borne in mind that the method as applied in heliometer observations gave very accurate results.

Prof. Cheshire said he hoped the author would turn his attention to the measurement of the entrance pupil, in other words, the effective aperture of the O.G. It is customary to fix a scale next the objective, and measure the image of it, but this image is not in the exit pupil, with the result that the circle has very fuzzy edges.

The author, in reply to Prof. Cheshire, said that in such a case it was customary to use an accurately machined diaphragm.

NOTICE

A Lecture on "The Story of a New Star" was given by Professor H. F. Newall F.R.S., on 10th March, 1921.

ABSTRACTS

"Coloured Glasses." By P. Senss, *Central-Zeitung f. Opt. u. Mech.* 41 (1920), 360.

The author explains the different designations of various types of coloured glasses and gives lists of the substances that are used for giving the different colours.

J.S.A.

"Neon Arc Lamps." By F. Skaupy, *Z. f. techn. Phys.* 1 (1920), 189.

The paper describes neon arc lamps manufactured by the Studien-Gesellschaft für elektrische Leuchtröhren m. b. H. Each lamp consists of a glass tube filled with neon at low pressure and provided with two or more electrodes. The cathode consists of an alloy of the alkali metals and other metals. The alloy is solid, even when the lamp is running. The lamp is designed for use with direct current at 220 volts; the current required is about 1 amp., a suitable resistance being introduced in the circuit. In order to strike the arc a vacuum interrupter is connected in parallel with the lamp, a small choking coil being inserted in the common portion of the circuit. An inductive impulse, set up by the automatic action of the interrupter by means of a magnetic coil, causes a discharge through the lamp. The colour of the light given out by the lamp is red and is therefore specially suitable for advertising, signalling, and medicinal purposes. The lamp uses about $\frac{1}{2}$ watt per candle power and has the great advantage over other vapour lamps that it can be lit and put out very quickly (as often as 400 times a minute).

J. S. A.

"Two Instruments for Focal Length Determinations." By Ch. v. Hofe, *Z. f. techn. Phys.* 1 (1920), 191.

The author describes two new forms of focometer made by C. P. Goerz.

(1) Ocular focometer. This instrument is designed so as to allow of the rapid and accurate determinations of short focal lengths, such as those of eyepieces. A glass plate with two lines engraved on it is placed in the focal plane of a camera objective, the axis of which is vertical; the plate is in a vertical plane and a mirror is employed to reflect the light through 90°. Above the objective is an iris diaphragm, and the eyepiece to be measured is held by an excentric clamp in a small adjustable table above the diaphragm. The distance between the images of the two lines formed in the focal plane of the eyepiece can then be measured by means of a scale in the focal plane of an observing eyepiece, which is held in a small table, adjustable in a vertical direction. The distance may also be measured by traversing the observing eyepiece by means of a micrometer screw. If a is the distance between the two lines, a' the distance between their images, α the angle between the bundles of rays from the lines, f and f' the focal lengths of the camera objective and eyepiece under test, respectively, then

$$\frac{a}{2} = f \tan \frac{\alpha}{2} \text{ and } \frac{a'}{2} = \frac{f'}{f} \cdot \frac{a}{2}.$$

By choosing suitable values of a and f the values of f' may be read off directly. It is advisable to adjust the paths of the rays through the eyepiece to be the same as in the complete instrument of which the eyepiece is a part. This can be done by moving the eyepiece in a vertical direction until its exit pupil lies in the plane of the iris diaphragm, and adjusting the size of the diaphragm opening to be equal to the exit pupil of the complete instrument. The distortion of an eyepiece may be determined by using as the

object a plate on which are engraved a series of pairs of marks at distances corresponding to fields of 5°, 10°, 15°, etc., and measuring the distances between the images of these marks. In order to measure the focal lengths of Huygenian eyepieces or of negative combinations a projection system working at unit magnification may be inserted between the scale and the system to be measured.

(2) Objective comparator. This instrument is used for comparing the focal lengths of objectives with those of standards. The objective under test and the standard objective are mounted in tubes having a common horizontal axis, so that each forms with an eyepiece and graticule a complete telescope. The graticule scales, which can be illuminated by flash lamps, consist in one case of two marks at a given distance g apart and in the other case of two double marks, the distance between the centres of which is also g. If, now, the focal lengths of the two objectives are equal, the images of the first two marks will fall exactly between the two double marks. If, however, the focal lengths are f and $f + df$, and the difference between the separations of the two sets of marks as seen in the focal plane of the second graticule is dg, then the difference in focal lengths is given by

$$\frac{f}{g} = \frac{f + df}{g + dg} \text{ or } df = f\,\frac{dg}{g}.$$

The value of dg may be measured by means of a micrometer eyepiece. Thus, if the focal length of the standard is accurately known, the focal lengths of similar objectives may be determined to a high degree of accuracy.

J. S. A.